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Effect of Diffuse Radiation on the Performance of a Rotationally Asymmetrical Optical Concentrator

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***Abstract*— This paper evaluates the performance of a recently patented rotationally asymmetrical dielectric totally internally reflective concentrator (RADTIRC) under diffuse radiation. The RADTIRC has a geometrical concentration gain of 4.969 and two half acceptance angles of ± 30˚ and ± 40˚ along the x-axis and z-axis respectively. Simulation and experimental work have been carried out to determine the optical concentration gain under diffuse radiation. It was found that the RADTIRC has an optical concentration gain of 1.94 under diffuse irradiance. The experimental results for the single concentrator showed an opto-electronic gain of 2.13, giving a difference of 9.8% due to factors such as the presence of direct radiation during experiments, the increase in diffuse radiation due to the reflection from surrounded buildings as well as from the ground reflection.**

Keywords — solar photovoltaic; building integrated photovoltaic systems; rotationally asymmetrical dielectric totally internally reflecting concentrator; opto-electronic gain.

I. INTRODUCTION

Building integrated photovoltaic (BIPV) systems can be a huge contributor to a carbon neutral household. Those systems generate electricity and function as structural elements of buildings simultaneously. According to Transparency Market Research [1], the annual installations of BIPV are expected to reach a capacity of 1152.3 MW by 2019. Regardless of the positive appearance and design advantages, high efficiencies and a good weather tightness, the viability of BIPV sytems is still low due to its high investment cost [2]. Reducing expensive solar cell material by concentrating sun light through cheap optical devices is a favourable way to minimise costs. Recently, new solar concentrator designs for BIPV have been introduced during the last decades with the aim of further reducing the installation cost of the BIPV systems. These applications are categorised as building integrated concentrating photovoltaic (BICPV) systems which typically employ low-concentration PV (LCPV) designs. To date, there are various designs by researchers which include symmetric and asymmetric compound parabolic concentrator (CPC) [3], 3D crossed CPC [4] and Square Ellipse Hyperboloid (SEH) concentrator [5].

The concentrator which was analysed numerically and experimentally in this work was proposed by Muhammad-Sukki *et al.* [6,7] and the patent has been granted recently [8]. It is categorised as a hybrid type concentrator, named rotationally asymmetrical dielectric totally internally reflecting concentrator (RADTIRC).

II. RADTIRC DESIGN

The RADTIRC is a variation of dielectric totally internally reflecting concentrator (DTIRC) and the process to design the RADTIRC has been discussed in detail in [6]. In contrast to the rotationally symmetric version, the RADTIRC is mirror symmetrical in two axes parallel to the base of the concentrator. Hence the entrance aperture is not a semi-hemispherical dome shape as in the DTIRC, but a faceted one, with different fields-of-view on different planes. The concentrator has a half-acceptance angle along the x-axis of ±30° representing the change of the solar altitude angle during the year. An example of a variation of the RADTIRC is presented in Figure 1. The

Figure 1: An RADTIRC sample.

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rays are refracted at the curved entrance aperture and reflected at the hyperboloid side profile towards the cell. The side profile along the z-axis is parabolic and has a half acceptance angle of ±40° which represents the change of the angle of incidence during the day. As a result, this concentrator does not require an electromechanical tracking system, but can capture sunlight during the year and during the day acting as a passive tracker [6].

III. SIMULATION

Figure 2 shows the diffuse light simulation setup. In order to obtain the optical concentration gain of the concentrator under diffuse light, a light source which generates rays coming from all directions is needed. As any object can be turned into a light source, a dome with a thickness of 1 mm and a 380 mm radius was created using AutoCAD. The radius corresponds to the distance between light source and concentrator during the direct light simulations [9]. The dome was created by revolving a circle section around an axis instead of using the dome function implemented in AutoCAD, which consists of planar sections. Thus none of the emitted rays are parallel to each other which enhances the similarity between the simulations and real diffuse light conditions. The light source was set to emit 1 million rays at a power of 1000 W. The concentrator, the layer of index matching gel and the detector are placed at the edge of the dome.

Considering that diffuse light is not directional, the optical concentration gain for the diffuse light is not a function of the incident angle of light. Therefore the concentration ratio for diffuse light is determined only at 0˚. The total power at the detector is obtained with and without the concentrator. The optical concentration gain is defined in the same way as the opto-electronic gain i.e. by dividing the total power at the detector with the concentrator by the one obtained without the concentrator [10].

The illumination under diffuse light does not have strong points of concentrated rays. Furthermore, as diffuse irradiance is not directional, the rays enter the concentrator at different angles of incidence. Although additional rays come from the side profile of the concentrator, the optical concentration gain is distinctly lower than for direct light simulations achieving an optical concentration gain of 1.94. The optical concentration gain for direct light is 4.66 [9] and thus higher by a factor of 2.4. This is because the concentrator design was optimised for direct irradiance and the field of view is therefore limited.

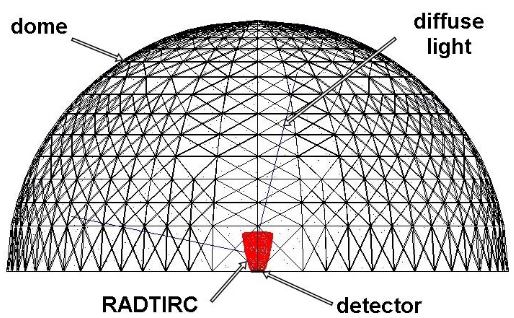

Figure 2: Diffuse light simulation setup.

Using the optical concentration gain definition, an optical efficiency of 41% was calculated. However this includes rays coming from the sides and not only through the entrance aperture as the definition describes by Welford and Winston [11]. To be able to compare the optical efficiency with other proposed concentrators for BICPV systems, the simulation was repeated with a 'box' covering its sides. This results in an optical efficiency of 35%. The SEH concentrator proposed by Sellami [5] achieved an optical efficiency between 27% and 41% depending on the concentrator's height. It is observed that the optical efficiency of RADTIRC for diffuse light concentration is also within the same range as the SEH concentrator. Since the optical efficiency for direct light is distinctly better, reaching 95%, it emphasises that the RADTIRC was optimised for direct irradiation. For a better performance of the concentrator under diffuse light, a larger entrance aperture as well as a larger acceptance angle is needed.

IV. EXPERIMENT

The performance analysis of the concentrator under diffuse light was carried out outdoors, as the necessary equipment to reproduce diffuse light conditions indoors is not available. The experiments (shown in Figure 3) were carried out within the Glasgow Caledonian University area on a roof top which is surrounded by other buildings. (55.866°N, 4.250°W) The set up includes the RADTIRC-PV device, a non-concentrating PV cell device, a pyranometer, an inclinometer, a thermometer and 3 multimeters. For the experiment, the cell with the concentrator and the non-concentrating PV cell were connected to a multimeter. With a thermo-couple thermometer, a temperature of 13°C was recorded. The slope of the location used is 0.5° towards south measured with a digital slope meter. An Apogee SP-110 pyranometer was used to measure the global irradiance.

The exact amounts of direct and diffuse light can be calculated when the sun angle is known, which can either be determined manually or using the software tools. The k_T factor in the experiment was 0.145 which proves that the amount of diffuse light was high during the experiments.

For a measured global irradiance of 70.5 Wm^{-2} and a sun angle of 20.92° at that particular time, a diffuse irradiance of 69.62 Wm^{-2} was calculated. This means that at the moment of the experiment, direct irradiance made up 1.3% of global irradiance. For a comparison, meteorological data from the Met Office Glasgow were consulted, where readings came from a site which is located approximately 18 km west of the location used for the experiment. The data from the Met station for the same hour was 78.9 Wm^{-2} and have therefore an amount of 1.6% of direct light irradiance.

The obtained opto-electronic gain is 2.13. This compared with the simulation result which is 1.94 gives a difference of 9.8%. For outdoor experiments, there are many factors influencing the opto-electronic gain which need to be considered. Firstly, the amount of direct light increases the opto-electronic gain. 1.3% of direct light is concentrated about

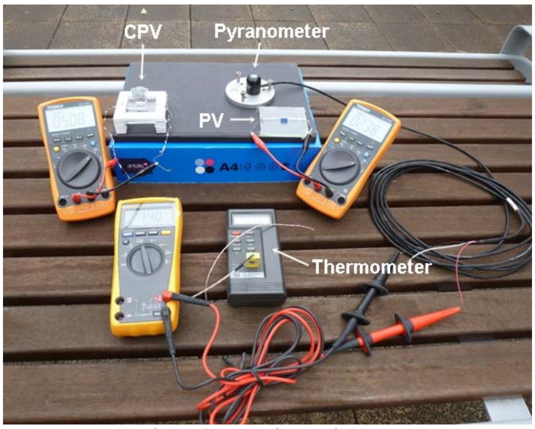

Figure 3: Experimental setup.

2.5 times more than the diffuse light and as a result direct light makes up about 3% of the overall concentrated light which reaches the solar cell. Secondly, the site where the experiments were carried out is surrounded by buildings, which have a high reflectivity due to the outer coating and window glass. The concentrator accepts light not only through the exit aperture but also from the sides, which increases the active area in comparison to the flat solar cell. The estimation of reflectivity of the buildings is based on the reflectivity values of the material and the colour. The reflectivity of fairly new concrete is taken to be between 30% and 40% [12], the reflectivity of glass as 7% [13] and the reflectivity of overall painting as 80% according to the light reflectance value (LRV) scale [14].

Another influencing factor is the ground reflection. Ground reflection is not considered for horizontal surfaces thus for the non-concentrating solar cell device. However, the side profile of the concentrator represents a tilted surface which accepts light. The calculated ground reflected irradiance of 8.87 Wm^{-2} is an additional irradiance, which acts only on the concentrator and not on the solar cell. This further explains the difference between the experimentally determined and simulated concentration gain.

CONCLUSIONS

The performances of the RADTIRC under direct and diffuse light conditions were investigated thoroughly in this paper. The optical concentrator for low concentration photovoltaic systems has a geometrical concentration gain of 4.969 and two half acceptance angles of $\pm 40^\circ$ along the z- axis and $\pm 30^\circ$ along the x- axis.

Simulation work was carried out to evaluate the optical concentration gain of the concentrator under diffuse irradiance. Using a ray tracing technique, an optical concentration gain under diffuse irradiance is determined to be 1.94. The simulation results were validated experimentally outdoor under diffuse light conditions. The experimental result showed an opto-electronic gain of 2.13, giving a difference of 9.8% when compared with the simulation, mainly due to factors such as the presence of direct radiation during experiments, the increase in diffuse radiation due to the reflection from surrounded buildings as well as from the ground reflection.

It can be concluded that the RADTIRC has the ability to improve the performance of BICPV systems by increasing the electrical output when compared to a non-concentrating PV module with the same volume of PV material. Savings in PV material, increased natural illumination and heat generation make the implementation of BIPV systems more attractive. Therefore the BICPV technology can contribute to more carbon neutral buildings, an increased technology efficiency and more renewable energy generation.

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